No deficiency in left-to-right processing of words in dyslexia but evidence for enhanced visual crowding.

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Abstract

Whitney and Cornelissen (2005) hypothesized that dyslexia may be the result of problems with the left-to-right processing of words, particularly in the part of the word between the word beginning and the reader's fixation position. To test this hypothesis, we tachistoscopically presented consonant trigrams in the left and the right visual field (LVF, RVF) to 20 undergraduate students with dyslexia and 20 matched controls. The trigrams were presented at different locations (from -2.5° to + 2.5°) in both visual half fields. Participants were asked to identify the letters and accuracy rates were compared. In line with the predictions of the SERIOL model of visual word recognition (Whitney (2001), a typical U-shaped pattern was found at all retinal locations. Accuracy also decreased the further away the stimulus was from the fixation location, with a steeper decrease in the LVF than in the RVF. Contrary to the hypothesis, the students with dyslexia showed the same pattern of results as the control participants, also in the LVF, apart from a slightly lower accuracy rate, particularly for the central letter. The latter is in line with the possibility of enhanced crowding in dyslexia. In addition, in the dyslexia group but not in the control group the degree of crowding correlated significantly with the students' word reading scores. These findings suggest that lateral inhibition between letters is associated with word reading performance in students with dyslexia.

Key words: dyslexia – visual word recognition - letter position encoding - SERIOL model - crowding - lateral inhibition

Introduction

Although advanced readers experience little difficulty deciphering words and text, reading is a complex process. It involves the rapid integration of orthographic, phonological, morphological, and semantic information. Problems with any of these elements may lead to a failure or a delay in the entire process. The complexity becomes particularly clear when we are confronted with children having difficulties in learning to read and/or write. When no sensory deficit can explain the reading and/or writing difficulties and when adequate tuition has been given but fails to result in an adequate level of performance, developmental dyslexia is diagnosed.

There is strong evidence that individuals with dyslexia have phonological difficulties (de Jong & van der Leij, 1999; Griffiths & Snowling, 2002; Vellutino, Fletcher, Snowling, & Scanlon, 2004; Wagner & Torgesen, 1987). These deficits have been described extensively in both children and adults with dyslexia (Bruck, 1992; Vellutino et al., 2004; Wilson & Lesaux, 2001; Wolff & Lundberg, 2003). There is discussion, however, on a number of fronts, including whether phonological deficits are the only problem, whether they are the basic cause of dyslexia or a symptom of other underlying deficits (see Bishop, 2006; Blomert & Willems, 2010; Castles & Coltheart, 2004; Dehaene et al., 2010; Ramus & Szenkovits, 2008 for more information). Various authors argue that a single cognitive level account of dyslexia cannot explain its heterogeneity (Heim et al., 2008), nor can it explain the fact that some children with dyslexia do not exhibit phonological impairments (Bosse, Tainturier, & Valdois, 2007; White et al., 2006). Several authors have proposed models alternative to the phonological deficit hypothesis, and models containing more than one failing component. For example, Bishop (2006) set out a multifactorial view of dyslexia, in which several perceptual and cognitive impairments interact. Menghini et al. (2010) ran a study to test this multifactorial hypothesis and concluded that dyslexia is indeed a complex disorder that can be caused by multiple neuropsychological deficits. They observed that only 19% of the children with dyslexia in the sample they tested had a pure phonological deficit. Most of the children showed impairments at different levels such as executive functioning, visual-spatial perception, attention allocation, and combinations of the above. A similar conclusion was reached by Ramus et al. (2003) who observed that many participants with dyslexia had sensory and motor problems in addition to a phonological impairment.

There is some evidence to suggest differences in the earliest stages of visual word processing in people with dyslexia. Using MEG technology, Helenius, Tarkiainen, Cornelissen, Hansen, and Salmelin (1999) observed that the divergence in cortical activation between normal and dyslexic readers is apparent in the earliest brain signals specific to words: 80% of the dyslexic readers did not show the typical left hemisphere infero-temporal activation 150 ms post-stimulus when confronted with letter strings (as opposed to other symbols or faces). This brain area is often referred to as the visual word form area (Cohen et al., 2000; Dehaene, Cohen, Sigman, & Vinckier, 2005; Warrington & Shallice, 1980). Taroyan and Nicolson (2009) also reported abnormal brain activity in the visual word form area when participants with dyslexia were confronted with words and pseudowords. One cause of these abnormalities may be a deficit in the visual attention span of individuals with dyslexia (Bosse et al., 2007; Lobier, Zoubrinetzky, & Valdois, 2012). A second cause may be enhanced lateral masking (reduced performance on target identification when flanked by nearby stimuli), as proposed by several authors (Bouma & Legein, 1977; Martelli, Di Filippo, Spinelli, & Zoccolotti, 2009; Pernet, Andersson, Paulesu, & Demonet, 2009). Indeed, there is evidence that increased spacing of letters may be beneficial to readers with dyslexia (Perea, Panadero, Moret-Tatay, & Gomez, 2012; Zorzi et al., 2012).

Whitney and Cornelissen (2005) formulated another reason why early visual processes could be the core deficit in dyslexia, based on the SERIOL model of visual word recognition. This SERIOL (Sequential Encoding Regulated by Inputs to Oscillations within Letter Units) model is a detailed model of word processing, describing how the visual signals from the retina are converted into abstract representations that can activate lexical representations (Whitney, 2001; Whitney & Cornelissen, 2005). Such conversion must explain two aspects of visual word recognition: (1) how words are recognized independent of their position in the visual field (and the retina), and (2) how letter positions within words are retained. In the SERIOL model this is achieved by means of five hierarchical layers. For a full account of the SERIOL model, see Whitney (2001). We focus on those aspects that are related to the proposed impairment in dyslexia.

How can the SERIOL model contribute to the understanding of dyslexia? To understand this, it is necessary to know that the SERIOL model postulates a left-to-right word recognition process at the highest level, the lexical level. The letters of the words are encoded in such a way that the signals of the first letter fire before those of the second letter, which in turn fire before those related to the third letter, and so on, resulting in a letter activation pattern from left to right, adequate for lexical retrieval. The left-to-right firing of letters is called the location gradient. When a word is fixated at the first letter or presented in the right visual field (RVF), the location gradient is in line with the signals coming from the retina (called the acuity gradient). Indeed, it is well documented that stimuli require more time to be processed the further they are from the centre of the visual field, because visual acuity drops steeply away from the fixation point (Brysbaert & Nazir, 2005). The increase in processing time can already be observed for letters presented one or two positions away from the fixation location. The right part of Figure 1 shows the correspondence between the acuity gradient and the location gradient when a word is presented in the RVF.

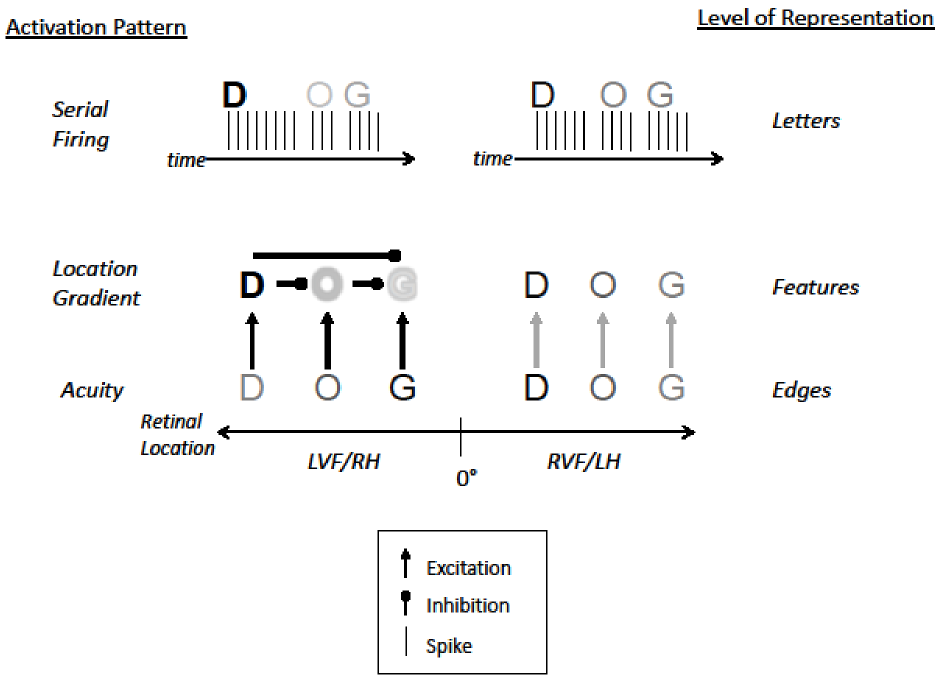


Figure 1. This figure portrays the activation patterns (left side) at the different levels of representation (right side) of the letters of the word "DOG" in each visual field, from retinal representation to activation at letter level. Darker letters represent higher activation levels, darker arrows represent stronger excitation. At the edge level, activation is based on acuity from fixation point (acuity gradient). At feature level, these levels of activation are transformed in a location gradient in the LVF due to stronger edge-to-feature excitation in the LVF/RH, and the left-to-right inhibition in the LVF/RH (blurriness of the letters). At the next level of representation -the letter level- the serial firing of the letters is represented as a spiking pattern. Each group of spikes represents the spiking duration for the letter above and the darkness of the letter (activation level) is in line the number of spikes for that letter. Based on the feature-level activity, the predictions for normal reading are that an initial letter should be recognized better in the LVF than the RVF, and an initial letter should have a stronger advantage over non-initial letters in the LVF than the RVF.

When the word is fixated at the last letter or presented in the left visual field (LVF), the acuity gradient is in contradiction with the location gradient, because under these circumstances the retinal signal is clearest/fastest for the last letter of the word, less so for the second-last letter, and so on. To reverse the acuity gradient into the location gradient, an inhibition process is postulated, such that the signals of the letters are inhibited until the signals of the preceding letters have fired. The left part of Figure 1 shows how the acuity gradient of a word presented in the LVF is reversed into the appropriate location gradient.

Further factors taken into account by the SERIOL model are that the retinal signals not only depend on the distance from fixation, but also on whether they come from letters on the outside of a word or from inner letters. The signals from exterior letters are stronger/faster because they are not fully surrounded by other letters. In addition, the firing of the last letter is not terminated by a subsequent letter.

A strong aspect of the SERIOL model is that it is mathematically formulated, so that it makes precise predictions about the chances of identifying the letters of tachistoscopically presented letter strings in both hemifields[1]. In the LVF, strong left to right inhibition is needed to turn the acuity gradient into the location gradient. In addition, there are the stronger signals from the exterior letters. Together these factors predict that the first letter of a word presented in the LVF will have the highest activation (even though it is furthest away from fixation), followed by the last letter, and the inner letters. There are two factors that influence the predictions on

[1] We restrict ourselves to the predictions made for small eccentricities, within -5°/5° of fixation, as these pertain to the present study. The letter perceptibility weights are slightly different for larger eccentricities.

identification patterns in the RVF, namely the presence of the acuity gradient and the higher activation levels for the exterior letters. Because the acuity gradient is less steep than the serial inhibition in the LVF, the pattern of results is expected to be more symmetric.

The predictions from the SERIOL model were confirmed in a tachistoscopic trigram identification experiment performed by Legge, Mansfield, and Chung (2001). These authors observed that in the LVF the first letter of the trigram had a much higher chance of being identified than the third letter, which in turn was identified more often than the middle letter. In the RVF, there was less difference between the accuracies for the first and the last letter, and both were better than the middle letter. The asymmetry between LVF and RVF is a function of the reading direction and reverses for languages read from right to left (Adamson & Hellige, 2006; Eviatar, 1999).

Because the conversion from the acuity gradient to the location gradient (for letters presented to the left of fixation) is a process specific to reading, Whitney and Cornelissen (2005) hypothesized that problems with its acquisition would lead to deficits very similar to those observed in dyslexia. More specifically, if people with dyslexia have a deficient location gradient, they would only be able to process the letters of the words in the right order when they are fixating on the first letter. Given that most words in reading are fixated towards the middle, the order of the letters to the left of fixation would be jumbled up and they would interfere with the processing of the letters to the right of fixation.

In summary,Whitney and Cornelissen (2005) hypothesized that the reading problems of individuals with dyslexia could be caused by a deficiency in the formation of the location gradient. Some empirical evidence consistent with this hypothesis was published by Pitchford, Ledgeway, and Masterson (2009). In a visual search task they reported that dyslexics reacted more slowly than skilled readers to target letters located on the left of the stimulus array. This could be interpreted as evidence for a deficient conversion of the acuity gradient to the location gradient in the LVF. In the present paper, we performed a more direct test of the hypothesis by comparing the performance of students with and without dyslexia on Legge et al. (2001) trigram recognition study. If the location gradient formation is indeed underdeveloped in students with dyslexia, the SERIOL model makes a straightforward prediction of how the pattern of results will differ in readers with dyslexia, as shown in Figure 2. Given that the acuity gradient agrees with the location gradient in the RVF and no inversion is needed, dyslexic readers should perform very similar to normal readers here, with better performance for the first and the last letter than for the middle letter. In contrast, given the importance of the location gradient formation in the LVF, the performance of the dyslexic readers should differ from that of the controls. In particular, they are not expected to show the strong advantage for the first letter of the trigram. Because of the acuity gradient we even predict that the last letter will be indentified more often than the other two letters.

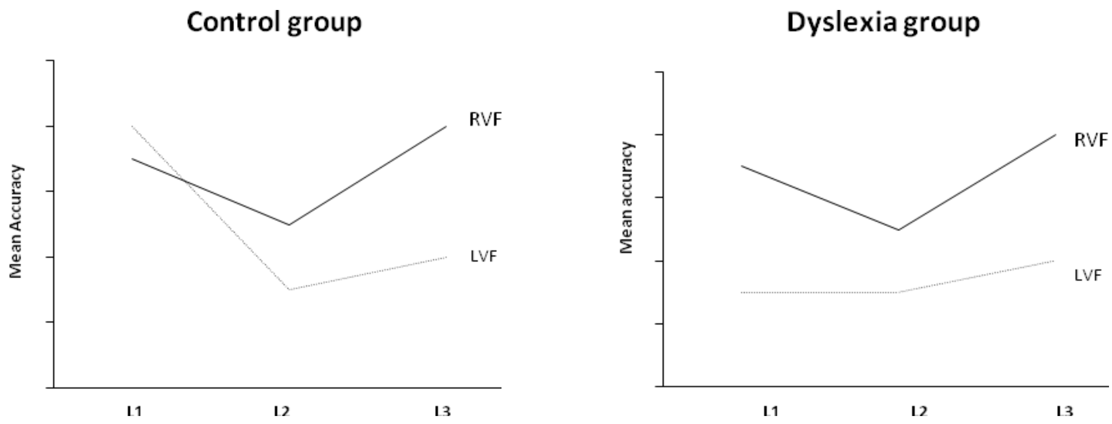


Figure 2. Expected mean accuracy rates in the right and left visual field for each group with a clear right visual field advantage for the last letter and a left field advantage for the first letter in normal readers. In readers with dyslexia the SERIOL model predicts an absence of this left field advantage for the first letter.

We tested the prediction outlined in Figure 2 by comparing the performance of a sample of 20 first-year bachelor students with dyslexia to a sample of 20 control students. We used the paradigm of Legge et al. (2001), in which trigrams of consonants were presented tachistoscopically at various positions in the LVF or the RVF. Participants had to identify as many letters as possible.

Method

Participants

Forty students in higher education (from the Association of Higher Education Ghent) received a small financial compensation for their participation in the experiment. All had normal or corrected-to normal vision and were native speakers of Dutch. They were first year students of either an academic bachelor (university and some academic colleges for higher education) or a professional bachelor (other colleges for higher education with less theory-driven teaching). The group consisted of 20 students diagnosed with dyslexia and a control group of 20 students with no known neurological impairments. All students were selected from the participants of a large scale study on dyslexia in higher education conducted at Ghent University, in which 100 students with dyslexia were compared to 100 matched control students on a battery of tests (Callens, Tops, & Brysbaert, 2012). Diagnoses of dyslexia were based on three criteria which are used by the Stichting Dyslexie Nederland (2008) [Foundation Dyslexia Netherlands]: (1) reading and/or spelling abilities are significantly below the level of performance expected for their age; (2) resistance to instruction despite effective teaching; (3) impairment cannot be explained by extraneous factors, such as sensory deficits. Table 1 shows the main characteristics of the groups. They were matched for age [$t(38) = -0.32$, $p = .75$] and intelligence [$t(38) = 1.03$, $p = .75$] as measured with the Kaufmann Adult Intelligence Test (Dekker, Dekker, & Mulder, 2004). Reading skills were assessed with a word reading and a pseudoword reading test. The word reading test was the Dutch One Minute Test (Brus & Voeten, 1991). A list of 116 Dutch words of increasing difficulty is presented in four columns. Participants have to accurately read as many words as possible in one minute. The pseudoword reading test was the Klepel (van den Bos, Spelberg, Scheepsma, & de Vries, 1999). The principle is the same as in the One Minute Test but instead of words pseudowords are presented. Writing skills were assessed with a standardized word spelling test for adolescents and adults, comprising of 30 words (De Pessemier & Andries, 2009). On all three tests the control group obtained scores within the normal range, whereas the students with dyslexia on average had scores more than 1.5 standard deviations below this level (see the effect sizes in Table 1).[2] Of the 20 students with dyslexia, two had a comorbid hyperactivity disorder.

Table 1

Characteristics of the 20 Control Students and the 20 Students with Dyslexia

		Control students	Dyslexia students	
Gender	Male	8	7	
	Female	12	13	
Institution	University	13	9	
	College	7	11	
Handedness	Right	19	14	
	Left	1	6	
		Mean (SD)	**Mean (SD)**	**Effect size (d)**
Age		19.20 (0.69)	19.20 (0.79)	NA
TIQ		110.75 (9.70)	109.85 (7.88)	0.10
OMT		59.2 (28.12)	18.22 (21.47)	-1.70
Klepel		57.34 (30.28)	17.09 (19.43)	-1.61
Word dictation		59.75 (27.00)	17.6 (18.90)	-1.65

Note. TIQ= Total IQ score; OMT= Dutch word reading, calculated from centile scores of the number of words read correctly in 1 minute time; Klepel= pseudoword reading, calculated from centile scores of the number of pseudowords read correctly in 1 minute time. Effect size calculated according to Cohen's d.

Design and stimuli

The stimuli consisted of consonant trigrams typed in upper case Courier New Font, size 24, composed of 3 consonants (see the appendix). The trigrams never contained two of the same

[2] Five students from the group with dyslexia performed significantly worse on the spelling test than on the reading tests. To make sure that our findings were not distorted by this subgroup, we repeated the analyses with the scores of the remaining 15 dyslexic participants. The results were the same as the ones reported here.

consonants and no two visually similar consonants were juxtaposed. By using trigrams, we minimized top-down contributions from phonology, lexicality, or semantics, so that the results maximally reflect the contribution of orthographic (visual) processing. The stimuli were presented at 11 horizontal retinal locations going from 5 letter positions to the left of fixation to 5 letter positions to the right of fixation (distances measured to the letter in the middle of the trigram). Participants were sitting at a distance of 60 cm from the screen, so that each letter subtended 0.5° of visual angle and the stimuli were presented from -3.0° in the LVF (the first letter of the most leftward stimulus location) to +3.0° in the RVF (the last letter of the most rightward stimulus location). The stimuli were presented briefly and participants were asked to type in the letters they perceived. Because interactions are difficult to interpret in the presence of large main effects (Loftus, 1978), we decided to work with individually adjusted stimulus presentation times. This also avoided ceiling and floor effects (Adamson & Hellige, 2006). The experiment began with practice blocks, each consisting of 18 trials. Trials in the first block used a stimulus duration equivalent to one refresh cycle of the monitor, namely 14 ms. After each block, the stimulus duration was increased by one refresh cycle until an accuracy rate of 70 % was reached. Once the threshold was acquired, the experiment started, using this presentation duration. Two blocks of 90 trials were presented. Per participant, the mean accuracy per letter and location was calculated.

Procedure

Participants completed the experiment individually in a quiet, well-lit room. They were seated in front of a computer screen at a distance of 60 cm. Detailed instructions were given on three subsequent screens. The participants were asked to concentrate on the fixation location, indicated by a flashing fixation cross ("+"). This fixation cross was obtained by six times presenting a "+" for 90 ms followed by a blank interval of 90 ms. The trigram stimulus was presented after the last blank interval, followed by a string of hash marks to mask the stimulus. The mask remained on the screen until the participant responded. The task of the participants was to type in the letters they had perceived. They were told that the speed of the response and the order of letters were unimportant. After the response was entered, there was a one second interval before the next trial was presented. Whenever the participants wanted to take a rest, they could pause the block.

Results

Presentation duration

For each participant, the presentation duration needed to obtain an accuracy level of 70% during the practice trials was noted. To compare the presentation times (expressed in milliseconds) of the groups, the data was first tested for normality using a Kolmogorov-Smirnov test expressed with the test statistic D. Data distributions for the control group [M = 70.6 ms, SD = 17.3 ms; $D(20) = .301$, $p < .01$,] and the group of participants with dyslexia [M = 78.2 ms, SD = 13.4 ms; $D(20) = .27$, $p < .01$] were significantly non-normal, so we used the non-parametric Mann-Whitney-U test for data analysis. The presentation durations between the two groups needed to reach 70% levels of accuracy were not significantly different [$U = 243$, $p = .244$].[3]

[3] In the next sections it will become clear that our procedure did not completely succeed in getting equivalent levels of performance in the group with dyslexia and the controls. If full equivalence is required, it may be better to adjust the stimulus duration as a function of the accuracy level throughout the entire experiment. Another way to better match the performance

Results for the main hypothesis

To test the main hypothesis of this study - namely that readers with dyslexia have a different letter identification pattern in the LVF due to impaired inversion of the acuity gradient into the location gradient - we ran an ANOVA with letter position (initial letter L1, middle letter L2, final letter L3) and trigram location (Location 1 to Location 9: Loc1 to Loc9) as repeated measures variables and group (normal, dyslexic) as a between subjects factor on the mean percentage correct scores. The assumption of homogeneity of variance was found valid on the basis of the Levene test. Our hypothesis predicted an interaction between letter position, trigram location, and group, but this effect was not significant [$F(16,23) = 1.290$, $p = .282$].

To better test the prediction outlined in Figure 2, we averaged the data per visual field. For the LVF we calculated the mean accuracies of trigram locations 1 to 4; for the RVF we grouped the trigram locations 6 to 9. An ANOVA on this new variable was run with visual half field (RVF, LVF) and letter position (initial letter L1, middle letter L2, final letter L3) as repeated measures and group (normal, dyslexic) as a between subjects variable. As can be seen in Figure 3, the performance of the participants with dyslexia was very similar to that of the control participants, both in the LVF and the RVF. In particular, the participants with dyslexia did not perform less well on the first letter (L1) in the LVF, as expected on the basis of Whitney and Cornelissen (2005). The interaction group x visual half field x letter position was not significant [$F(2,37)= 0.252$, $p= .78$] and a likelihood ratio test (Dixon, 2003) confirmed that a model with

levels may be to use a screen with a higher refresh rate than the presently used 70 Hz, so that finer adjustments can be made. Our adjustments were inspired by the consideration that large differences in overall performance would make the interpretation of interaction effects difficult, and we succeeded in the objective of avoidance them.

the interaction of letter position x VF x group was as likely as a model without this interaction (L= 1.02; only values above 10 would point to a contribution of the interaction).

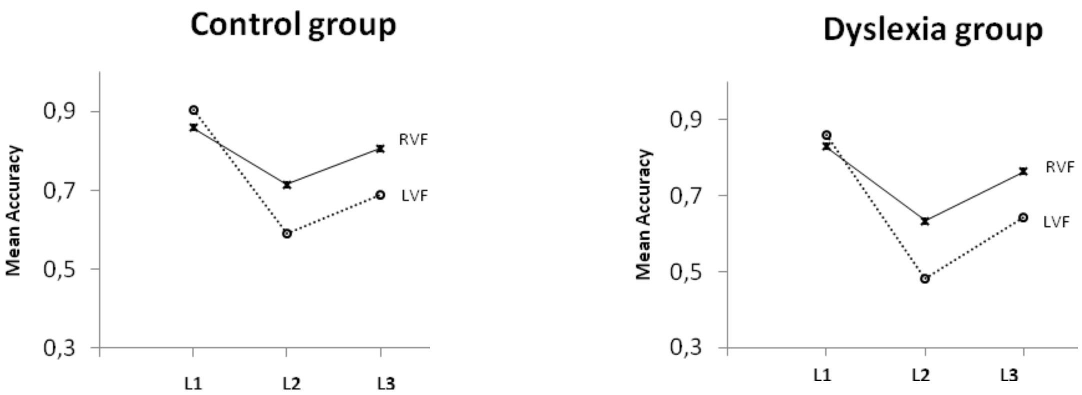
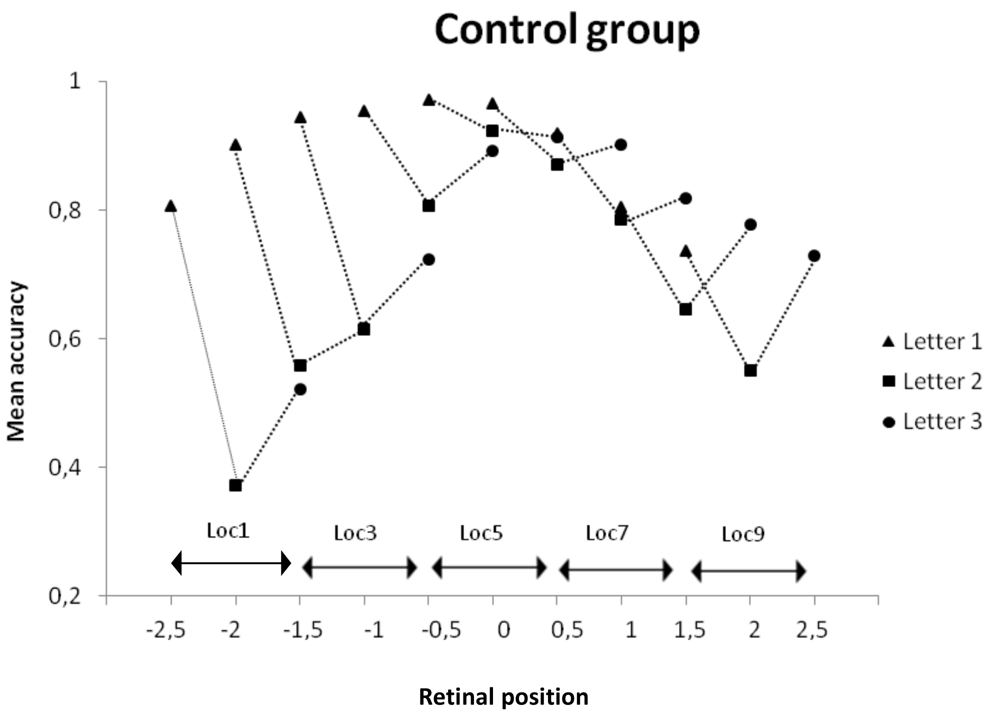


Figure 3. Mean accuracy for the three trigram letters for the left visual field and right visual field presentation for the two groups. The figure shows the lower accuracy level for all letters in the dyslexic group compared to the control group. As mentioned in the results, the graphs also illustrate the RVF advantage for L2 and L3 in both groups. In L1 this pattern is reversed for both groups. Most importantly, however, the dyslexia group did not show the drop in performance for L1 in LVF, as predicted in figure 2.

Other main and interaction effects

The ANOVA with letter position, ***trigram location***, and group revealed a significant main effect of group [$F(1,38) = 6.984$, p =.012]. Participants with dyslexia overall had lower accuracy scores than normal readers (73% (SD=1.4) versus 78% (SD=1.4)). The ANOVA also yielded main effects of letter position [$F(2,37) = 279.88$, $p < .001$] and trigram location [$F(8,31) = 99.19$, $p < .001$]. As can be seen in Figure 4, the main effect of letter position showed the typical U-shaped pattern at almost all retinal locations in both groups. With respect to the main effect of trigram location, we found the expected increase in accuracy when stimuli were presented close to the fixation location. The decrease in performance as a function of eccentricity was steeper in the LVF than in the RVF. Turning to the main effect of letter position, performance was better on L1 than on L2 [$t(39) = 22.012$, $p < .001$], on L3 than on L2 [$t(39) = 8.470$, $p < .001$] and on L1 than on L3 [$t(39) = 15.06$, $p < .001$].



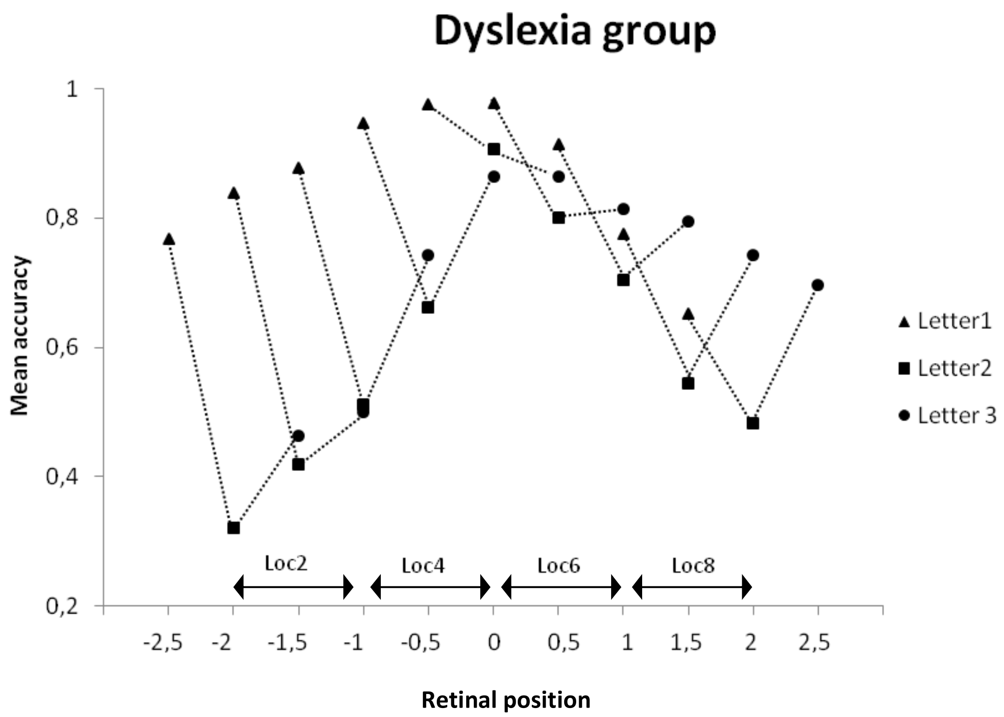


Figure 4. Mean accuracy of each of the three trigram letters at different locations from -2.5° to 2.5° of fixation point.

In addition to these main effects, there were two significant interaction effects: letter position x group [$F(2,37) = 4.168$, $p = .023$] and trigram location x letter position [$F(16,23) = 20.818$, $p<.001$]. The letter position x group interaction was explored with follow-up ANOVAS; these indicated that performance between the groups did not differ on L1 [$t(38) = 1.679$, $p=.101$, d = .5], was marginally worse on L3 [$t(38)= 2.120$, $p = .041$, d = .6], but differed significantly on L2 [$t(38) = 3.539$, $p = .001$, d = 1.4]. Because the observed trigram location x letter position interaction [$F(16,23) = 20,818$, $p < .001$] is in line with the SERIOL predictions and is not of particular interest to the idea tested in this paper, we do not present a detailed description.

The ANOVA with letter position, ***visual half field***, and group replicated the main effect of group [$F(1,38)= 7.153$, $p= .01$]. It further revealed a clear RVF advantage [$F(1.38) = 58.609$, $p < .001$], which was present in both groups as the interaction group x visual field (VF) was not significant [$F(1,38) =0 .728$, $p = .399$]. A RVF advantage for letter perception has been reported several times before (e.g., Hellige, Taylor, and Eng (1989) Hellige, Cowin, and Eng (1995) and is related to the typical left hemisphere dominance for language processing (Hunter & Brysbaert, 2008). There was a main effect of letter position [$F(2,37)= 291.21$, $p < .001$], which interacted with visual half field [$F(2,37)= 46.02$, $p < .001$] and with group [$F(2,37)= 4.52$, $p= .017$]. The interaction between letter position and visual half field was caused by the fact that the RVF advantage was only present for L2 [$t(39) = - 8.852$, $p < .001$] and L3 [$t(39) = - 7.213$, $p < .001$]. For L1, there was a reversed visual field advantage: The first letters of the trigrams were reported more accurately in the LVF than in the RVF [$t(39) = 2.773$, $p = .008$]. The interaction between letter position and group was due to the relatively worse performance on L2 in the dyslexic group. This finding is further examined in the next section.

The crowding effect

To further examine the worse performance on L2 in the dyslexic group and the crowding to which it could point, a new variable was constructed to express how much worse L2 was identified compared to L1 and L3. This was calculated per participant by subtracting the overall accuracy on L2 from the average accuracies on L1 and L3 across all stimulus locations [i.e., crowding= ($L1_{\text{mean accuracy}} + L3_{\text{mean accuracy}})/2 – L2_{\text{mean accuracy}}$]. As expected on the basis of the previous ANOVAs, a t-test on this crowding variable showed a larger difference between performance on the inner letter and the outer letters in the dyslexia group [*M*=0.18, *SD* =0.05] than in the control group [*M*=0.14, *SD*= .05; *t*(38)= -2.602, *p*=.013]. To gauge the potential importance of the difference, we calculated a Cohen's d effect size, which equalled to *d* = 0.8, so potentially a large effect (although one has to take into account the large confidence interval, given the small numbers of participants involved in the between-group comparison). The same variable was calculated for the two visual fields separately, and showed a larger crowding effect in the LVF (locations 1 to 4) than in the RVF (locations 6 to 9) [*F*(1,38)= 41.311, *p*<.001]. The larger crowding effect in the LVF was found for both groups (as the interaction with participant group was not significant; *F*(1,38) = 0.441, *p* = .511).

Correlations and linear regressions with reading scores

To see whether the enhanced crowding was connected to the reading skills in general, Pearson correlations were calculated between the crowding variable and the scores on the One Minute Test (word reading), the Klepel (pseudoword reading), and the word dictation test for the 40 participants. These revealed significant correlations with crowding for the reading tests (OMT: *r*= -.507, N = 40, p= .001; Klepel: *r*= -.393, N = 40, *p*=.012; word dictation: *r*=-.23, N = 40, *p*=.151). Further multiple regression analysis on the data from the dyslexia group with the scores on the OMT, the Klepel, and word dictation as predictors, indicated that only the OMT was a significant independent predictor of crowding in this group [*β* = -0.002, *CI95%* lower bound = -0.003, *CI95%* upper bound = -0.0001, *p* = .001].[4] The scores on the Klepel did not provide a

[4] To make sure that the correlation with OMT could be interpreted as the outcome of crowding, we additionally looked at the correlations between OMT and performance on each of the letter positions. This analysis conformed that the correlation OMT performance and L2 accuracy in the dyslexic group was significantly larger than the correlation between OMT performance and L1 accuracy (p=.006, Hotelling-Williams test, see (Steiger, 1980)) or the correlation between OMT and L3 accuracy (p=.059).

significant increase in prediction precision [*β*=0.136, *p*=.452], nor did the scores on the word dictation test [*β*=-0.105, *p*=.582]. The overall model fit was *R* = .257. A similar analysis on the data of the control group did not provide a significant predictor. Figure 5 illustrates the difference between the two groups.

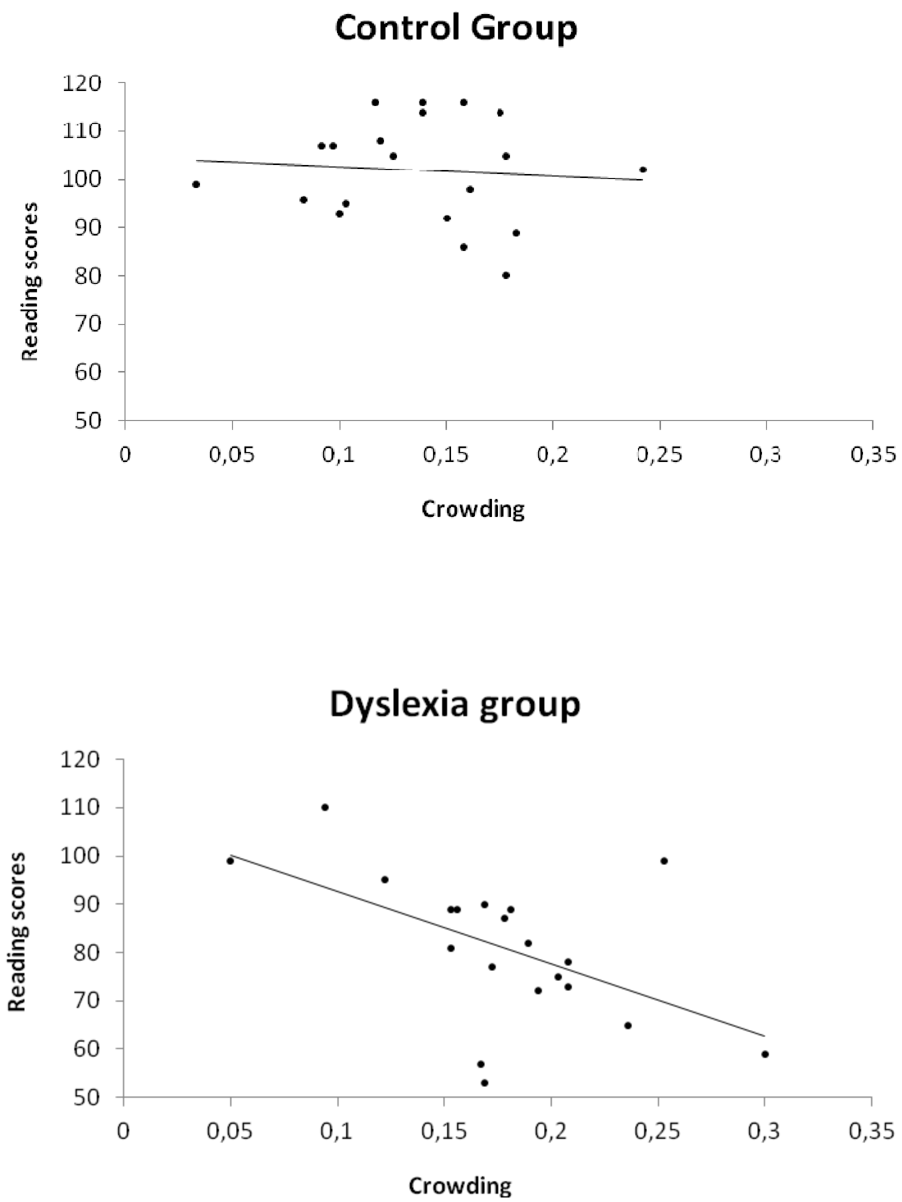


Figure 5. Scatter plots of the control group and the dyslexia group with on the X-axis the crowding effect and on the Y-axis the scores on the One Minute Test (Brus & Voeten, 1991). A linear trend line was added.

To further check whether problems with the formation of the location gradient could be a factor in the worst performing participants, we also calculated the correlations between a location variable defined as L1–L3 in the LVF (i.e., on stimulus locations 1-4) and the reading and writing scores. If the absence of the L1 advantage is the origin of reading problems, we should find that the difference between L1 and L3 is particularly small for poor readers. In other words, for the dyslexics we should find a positive correlation between reading skill and the difference between L1 and L3 in the LVF. No such correlation was found. As a matter of fact, the correlations trended in the opposite direction, with a slightly smaller difference for good readers than for poor readers, although the correlations were not significant (correlation between OMT and L1-L3 difference: $r = -.30$, $p=.197$, $N = 20$; Klepel: $r = -.17$, $p=.391$; word dictation: $r = -.06$, $p=.474$).

Discussion

In this paper we tested a hypothesis about the origin of dyslexia put forward by Whitney and Cornelissen (2005)on the basis of the SERIOL model of visual word recognition. According to the SERIOL model, visual word recognition involves a reading-specific skill (the inversion of the acuity gradient into the location gradient for letters presented to the left of fixation). Whitney and Cornelissen hypothesized that failure in acquiring this skill could be the true origin of reading problems (and the accompanying phonological deficits). To test this proposal, we repeated a study of Legge et al. (2001), in which consonant trigrams presented in the LVF and the RVF produced a pattern of results that was in line with simulations of the SERIOL model. Whitney and Cornelissen's (2005) hypothesis predicted a crucial difference between participants with dyslexia and controls for this particular task, as participants with dyslexia were expected not to show the high identification rate for the first letter in the LVF. For the rest, the performances were expected to be very similar (see the predictions laid out in Figure 2).

To test the hypothesis, two groups of participants were examined: one with normal reading/writing skills, and one with deficient reading/writing skills (Table 1). We were able to replicate the findings of Legge et al. (2001) in the group with normal skills (first part of Figure 3), providing evidence for the SERIOL model as a model of visual word recognition. However, contrary to the predictions of Whitney and Cornelissen (2005) we obtained very much the same pattern of results in the group with dyslexia (second part of Figure 3), suggesting that for the group of dyslexics we tested problems with the formation of the location gradient were not the origin of the reading problems. This is different from the finding with the visual search task reported by Pitchford et al. (2009), which pointed in the direction of reduced performance in the LVF for dyslexic readers.

The only significant difference we found between the dyslexic and the control group was worse performance on the middle letters of the trigrams (L2), suggesting an enhanced crowding effect in poor readers. Bouma (1970) was amongst the first to report inferior identification of embedded letters compared to letters in isolation, a phenomenon referred to as lateral masking or crowding (Bouma, 1973; Brysbaert & Nazir, 2005; Huckauf, Heller, & Nazir, 1999; Huckauf & Nazir, 2007; Massaro & Cohen, 1994; Pelli et al., 2007). Lateral masking is thought to occur at the first stages of visual processing before the letters are identified (Huckauf et al., 1999; Huckauf & Nazir, 2007). The extent of lateral masking is influenced by three factors: (1)

the distance of the stimulus from fixation, (2) the distance between adjacent letters, and (3) the similarity between letters. Lateral masking is largest when the stimulus is far from fixation, the letters are close to each other and similar to one another. Bouma and Legein (1977) further reported an enhanced crowding effect in readers with dyslexia, a finding replicated by several authors (Goolkasian & King, 1990; Klein, Berry, Briand, Dentremont, & Farmer, 1990; Martelli et al., 2009; Pernet, Valdois, Celsis, & Demonet, 2006). Moores, Cassim, and Talcott (2011) argued that the enhanced crowding effect in dyslexia could be due to a deficit in attention allocation or to an unusually high lateral inhibition. For an alternative hypothesis of crowding in terms of letter position encoding see also Collis, Kohnen, and Kinoshita (2012).

An obvious next step was to correlate the crowding effect of the participants to their reading and writing scores as measured with a word reading test (OMT), a nonword reading test (the Klepel), and a word dictation test. We indeed observed in our dyslexic students (but not in controls; Figure 5) that enhanced crowding correlated with word reading performance (more than with nonword reading performance and word dictation), further suggesting a link between both variables, in line with the recent demonstration that increased letter spacing helps children with dyslexia more than control children (Perea et al., 2012; Zorzi et al., 2012). Further analyses confirmed that the correlation was limited to the crowding effect, as the correlation between word reading performance and accuracy scores on the middle letter in the dyslexic group was significantly larger than the correlation between word reading performance and accuracy on the first letter and last letter. Thus performance on the middle letter correlated best with the reading scores.

Although it is tempting to interpret the correlation between dyslexia and degree of crowding as suggesting that crowding is the cause of dyslexia, it is important to keep in mind that this interpretation may not be correct. Grainger, Tydgat, and Issele (2010) reported a larger crowding effect for symbols than for letters in normal readers and hypothesized that the smaller crowding effect for letters is letter-specific and the consequence of a specialized system acquired as part of learning to read. On the basis of this finding, a plausible, alternative interpretation of the larger crowding effect for dyslexics in our experiment may be that it is a consequence of less reading experience, rather than a cause of the reading problem.

Returning to the main question addressed in this study, we were unable to find evidence for Whitney and Cornelissen's (2005) hypothesis that the reading problem in dyslexia is due to a deficit in the left-to-right processing of words. There was no indication that students with dyslexia were less efficient at inversing the acuity gradient in the LVF than the controls. As a result we can conclude that problems with the location gradient are *not the only* cause of dyslexia. Whether we should conclude that it plays no role at all depends on the extent to which the participants we tested are representative of all people with dyslexia. Our sample performed considerably below expected levels on tests of reading and spelling, and all had a confirmed diagnosis of dyslexia. Nevertheless, they were a relatively high-achieving group, having compensated sufficiently to have started undergraduate studies. In terms of a multifactorial view of dyslexia, it remains possible that for some people, an impairment in the ability to inverse an acuity gradient into a location gradient for letters to the left of fixation is a possible cause of their dyslexia. As this might be associated with more severe reading difficulties, future studies should repeat our test with younger people with dyslexia, to see whether they all show the normal pattern, as seen in the adults with dyslexia in this experiment, and if not, to monitor the reading progress in children showing a deviant pattern.

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Appendix

Stimulus list

BCZ / CGV / DPW / GJN / HPS / JXB / LJH / MTJ / PMK / TFZ / BHP / CKT / DSC / GLZ / HRG KGV / LNS / NFD / PVK / TXB / BHF / CSJ / DTG / GPF / HXS / KJM / LVZ / NGM /PZW / VGB BJZ / CVP / DWB / ZMG / HXT / KLX / LTB / NHW / RGX / VKM / BSF / CXM / FBX / GSW HXW / KRN / LWF / NJW / RHD / WJD / BXM / DBX / FXN / GZH / JGN / KVR / MCN / NTJ RKN / WTK / BZJ / DHM / GCZ / HCR / JMC / LDJ / MGF / NVM / SKX / ZBS / BZK / DLC / GHB / HFR / JNB / LDN / MPD / PCJ / SWJ / XBV / CDB / DNW / GHT / HMD / JPX / LHC / MRD / PDT / TBR / ZVC